Neutron Radiographic Techniques, Facilities and Applications

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NEUTRON RADIOGRAPHIC TECHNIQUES, FACILITIES AND APPLICATIONS

J. C. Domanus

Abstract. This is a collection of three papers, written for presentation on two international conferences.

The first paper: "Neutron radiography.Techniques and facilities", written by J. P. Barton of N-Ray Engineering Co. La Jolla, CA., USA and J. C. Domanus was presented at the International Symposium on the Use and Development of Low and Medium Flux Research Reactors at the Massachusets Institute of Technology, Cambridge, Mass., USA, 16-19 October 1983.

The second paper: "Neutron radiography with the DR-1 reactor at Risø National Laboratory", written by J. C. Domanus, was presented at the same Symposium.

(continued on next page)

August 1984
Risø National Laboratory, DK-4000 Roskilde, Denmark

The third paper: "Defects in nuclear fuel revealed by neutron radiography", written by J. C. Domanus is accepted for presentation on 18 October 1984 to the 3rd European Conference on Nondestructive Testing, Florence, Italy, 15-18 October 1984.

While the first paper describes the principles of neutron radiographic techniques and facilities, the second one describes an example of such facility and the third gives an example of application of neutron radiography in the field of nuclear fuel.

INIS Despriptors: NEUTRON RADIOGRAPHY; NUCLEAR PULES

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October 16-19, 1983

NEUTRON RADIOGRAPHY

TECHNIQUES AND FACILITIES

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ABSTRACT

After describing the principles of the "in pool" and "dry" installations, techniques used in neutron radiography are reviewed. Use of converter foils with silver halide films for the direct and transfer methods is described. Advantages of the use of nitrocellulose film for radiographying radioactive objects are discussed. Dynamic imaging methods are shortly reviewed. Standardization in the field of neutron radiography (ASTM and Euratom Neutron Radiography Working Group) is described. Many of the low and medium flux research reactors are used for neutron radiography. The paper reviews European and North American NR installations together with their main fields of use. Future possibilities of use of neutron radiography at research reactors in various scientific, industrial and other fields are finally mentioned.

PRINCIPLES OF NEUTRON RADIOGRAPHY

All radiographic methods, whether making use of X-rays, gamma-rays or neutrons are based on the same general principle: that radiation is attenuated on passing through matter. The object under examination is placed in the incident radiation beam. After passing through, the beam that remains enters a detector that registers the fraction of the initial radiation intensity that has been attenuated. by each point in the object. Any inhomogeneity in the object or an internal defect (such as e.g. void, crack, porosity or inclusion) will show up as a change in radiation intensity reaching the detector.

Thus detection of defects in radiography is based on the observation of differences in radiation intensity after passing through the object under examination. This occurs according to the basic law of radiation attenuation:

$$J = J_o e^{-\mu x}$$

The radiation attenuation coefficient μ shows a continous curve for X-rays (over a wide range of wavelengths). This is not true, however, for neutrons and it happens that adjacent atomic number elements such as boron and carbon show for example marked differences in neutron attenuation. Because of this it is possible to detect hydrogen in zirconium. Conversly, dense materials such as lead, tungsten, or uranium are relatively easy to penetrate by neutrons. Another important advantage of neutron radiography is the possibility of examining radioactive objects such as spent fuel elements directly.

RADIATION SOURCES

There are three sources of neutrons available for neutron radiography: accelerators, radioisotopes and nuclear reactors. Only the latter will be reviewed below. At present nuclear reactors provide the most intense neutron beams and therefore can produce neutron radiographs of the highest quality.

Two types of neutron radiographic facilities are used with nuclear reactors. In the "in pool" facility the whole neutron radiographic installation is immersed in the pool of the reactor. Here, irradiated reactor fuel rods, removed from the reactor core, are transferred to the neutron radiographic facility, where they are examined without removing them from the reactor pool.

In the "dry" type facility a neutron beam taken out of the core of the reactor is used outside the reactor for neutron radiography.

NEUTRON RADIOGRAPHIC TECHNIQUES

As in X- or gama-radiography, X-ray film is the medium for producing neutron radiographs. For radiographying radioactive materials the nitrocellulose film is also used.

Unfortunately, neutrons have very little direct effect on photgraphic film. Thus an intensifying screen of some kind is needed to improve the speed of the film. The nitrocellulose film must also be

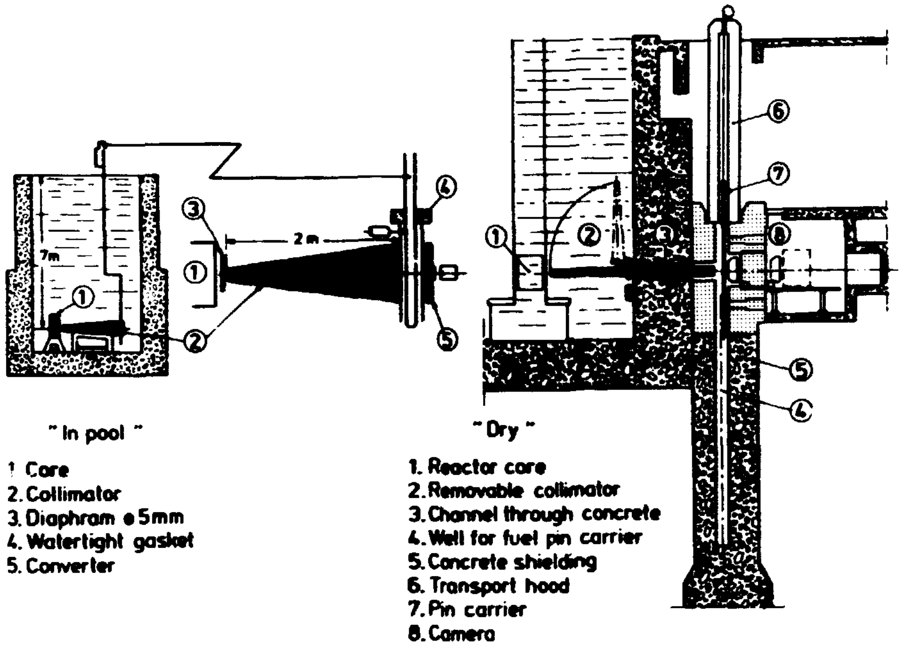

Fig. 1. "In pool" and "dry" reactor radiographic facility

used with a converter screen, as neutrons do not directly affect this type of film.

Of the many existing methods of recording neutron images, only those which are widely used in practice will be described here. They are the following: the direct and transfer technique using metal converter foils with X-ray film and the track-etch technique using nitrocellulose film. The properties of metals used as converter foils for the direct and transfer techniques are summarized as follows:

Material: $^{Nat}_{64}Gd$; $^{Nat}_{49}In$; $^{Nat}_{66}Dy$. Thermal neutron absorption coefficient: 140.3; 0.73; 3.01 mm^{-1}. Predominant nuclear reaction: (n,γ). Half-life of radiation emitter: prompt; 54 min; 2.5 h. Type and energy of radiation: $IC\beta^-$, 71 keV (main); β^-, 1.28 MeV (max); β^-, 1.00 MeV (max).

Information about other techniques used in neutron radiography can be found in numerous references on the subject (e.g., in [1,2,3,4].

Direct Exposure Technique

In the direct exposure technique a metal converter foil is placed in contact with X-ray film during the actual exposure (fig. 2). Usually, a single gadolinium back screen is used. This screen emits

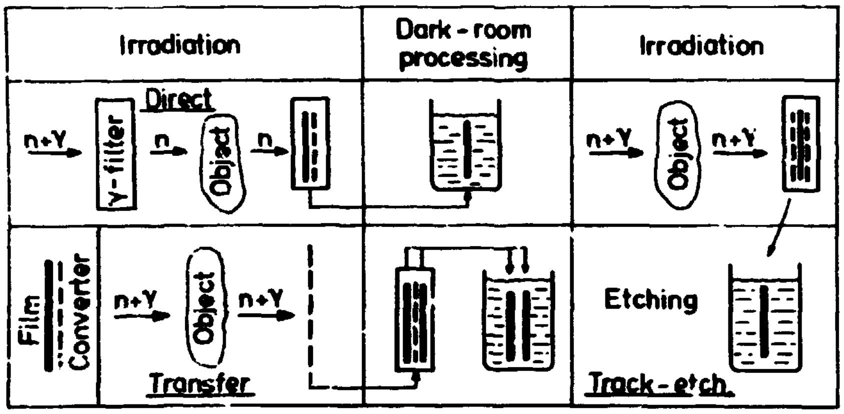

Fig. 2. Neutron radiographic techniques

gamma-radiation on absorbing neutrons. The gammas in the spectrum from gadolinium are suitable for producing electrons by internal conversion. Those low-energy electrons essentially expose only the emulsion facing the gadolinium. Single coated slow X-ray films are therefore used with the direct technique.

At present a single, 25 μm thick back screen is used. The screen is usually laminated to aluminium to facilitate handling. Vapour-phase deposited screens are also available, protected with a sapphire coating 1 μm thick. To assure good contact between the film and screen vacuum cassettes are used.

With the direct exposure technique, using Gd converter foil, a spatial resolution of about 12 μm can be achieved. A typical thermal neutron exposure for a slow, single coated X-ray film and a single 25 μm Gd screen is about 10^9 n.cm^{-2}.

Transfer Technique

In the transfer technique (fig. 2) only the converter screen is exposed directly to neutrons. The metal screen, placed in the neutron beam, becomes radioactive in proportion to the intensities in the spatial neutron image. The screen is subsequently transferred from the neutron beam to a dark room where it is placed in close contact with the X-ray film using a vacuum cassette. The radioactive emission from the screen then produces an image on the film.

For the transer technique a material must be chosen which is rapidly activated and has a rapid decay, so that it can be used again. Indium and dysprosium are the most commonly used materials.

The transfer method offers the advantage that the film, which is not present in the neutron beam, is not exposed to gamma-radiation from a radioactive object or from gamma-rays in the neutron beam itself.

The more energetic β-particles emitted by the transfer screens have sufficient energy to penetrate normal photosensitive film completely. Thus both emulsions of a double coated X-ray film will contribute appreciably to the film density and to the unsharpness. To avoid the latter it is important to use single coated films.

For the transfer technique mainly indium and dysprosium foils are used. Dysprosium is a harder metal and therefore easier to handle and maintain. It also has a higher thermal cross section and longer halflife. Therefore, it can be used with weaker neutron beams.

For a 100 μm Dy converter an exposure to neutrons of 3×10^9 $n.cm^{-2}$, followed by an exposure of several half-lives of the converter to a medium speed X-ray film, will be needed. A spatial resolution of 50 μm can be reached with a single coated film.

Track-etch Technique

For neutron radiography of radioactive objects (such as irradiated nuclear fuel) nitrocellulose film is used as a neutron detector. This is a dielectric material which can detect charged par ticles by the radiation damage caused in it. Those charged particles are produced by an α-emitting converter screen. The radiation damage is made visible by etching in hot sodium hydroxide solution (e.g., in 10% NaOH for 45 min at 50°C). The nitrocellulose film, sandwiched between two α-emitting converter screens, is placed directly in the neutron beam (fig. 2) as it is insensitive to gamma-rays. As the nitrocellulose film is also insensitive to visible light the consecutive etching need not be done in a dark room.

Nitrocellulose film is available (from Kodak-Pathé, France) for neutron radiography in two film/converter variations. The first consists of a 100 μm thick sheet of cellulose nitrate coated on both sides with lithium borate dispersed in a water-soluble binder, which acts as a converter screen by means of the (n,α) reaction (CN 85 Type B). After irradiation the lithium borate coating is removed by washing and then the film itself is etched.

The second variation consists of the same CN 85 nitrocellulose film (without coating) which is sandwiched between two converter screens (BN 1) made from natural boron, a (n,) converter. This converter is coated on a 100 µm thick, very stable, polyester base and can be reused indefinitely. The efficiency of the BN 1 is higher than that of the CN 85 Type B and therefore requires expo ure times only slightly longer than those for the transfer technique (with Dy converter and slow X-ray film). To establich perfect contact between the converter and nitrocellulose film the use of a vacuum cassette is essential.

When comparing nitrocellulose and X-ray films as media for neutron radiography one can see that although the contrast on the nitrocellulose film is weaker the definition is better. A spatial resolution of 25µ m can be obtained. In comparison to the transfer technique there is no saturation of the converter; this can be advantageous when using low-intensity neutron sources. There is no handling of an active converter, as in the transfer method. Finally, one shall mention the possibility of stopping the etching processing at intermediate stages. After evaluating the neutron radiograph at that stage the etching of the same nitrocellulose film can be further continued. Thus from a single exposure one can have several neutron radiographs of different densities and contrast.

VIEWING OF NEUTRON RADIOGRAPHS

Viewing neutron radiographs produced by the direct or transfer method on X-ray film creates no special problems. Neutron radiographs produced by the track-etch technique on the other hand are unsuited for direct viewing because of their low contrast. The contrast can be significantly improved by printing the film on a high contrast film, using a point source enlarger. However, the nitrocellulose film can be directly examined by placing it between two polarizing filters.

DYNAMIC IMAGING

Although methods of dynamic imaging could more appropriately be called neutron fluoroscopy than neutron radiography, they vill be shortly reviewed here. The principle of a TV system of neutron fluoroscopy is shown in fig. 3.

A more sophisticated sytem uses neutron image intensifier tubes [4] with a front gadolinium screen. The secondary electrons from it are accelerated on to a scintillator screen on which the neutron picture can be observed. This neutron tube (or neutron camera) can be used with a TV system (camera and monitor) to provide a remote display and recording.

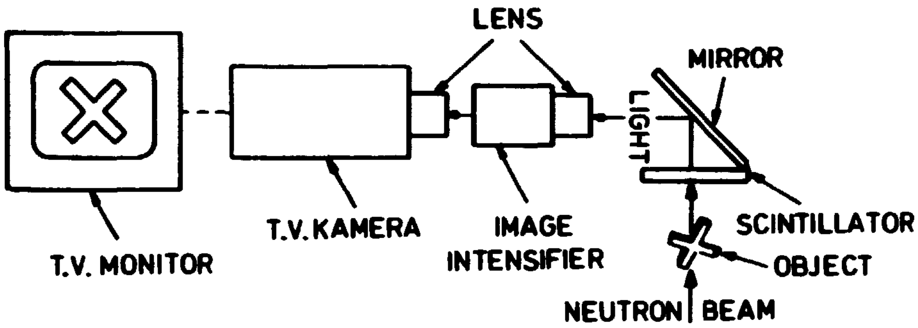

Fig. 3. TV neutron fluoroscopy

One of the most impressive applications of neutron fluoroscopy has been the cold neutron fluoroscopy of a running aircraft gas turbine engine or a car engine, in order to establish the dynamic distribution of the lubricating oil through the oil passages within the engine [4].

STANDARDIZATION

As neutron radiography is a relatively new technique there are only few standards in that field. Besides the ASTM standardization [5] the Euratom Neutron Radiography Working Group has started similar activity in 1979. As a result of this, a new edition of a neutron radiography atlas [6] will be published soon [7]. It will contain reference neutron radiographs of nuclear reactor fuel.

Under the NRWG test program beam purity and sensitivity indicators, together with a special calibration fuel pin [3] are tested at present in 14 facilities of the NRWG. The purpose of this program is to choose the best image quality indicators for neutron radiography of nuclear fuel and to determine with which accuracy and by which methods dimensions from neutron radiographs can best be measured.

REACTOR INSTALLATIONS

Reactor installations for neutron radiography can be categorized in various ways.

There are those installations (the majority) where the reactor already existed before planning of a radiography beam. There are some reactors, however, that were commissioned specifically for neutron radiography, such as the MIRENE reactors

TABLE I

Western Europe
Sample Neutron Radiography Projects

Country	Location	Reactor
Austria	Vienna	Triga
Belgium	MOL	BR1 BR2
Denmark	Riso	DR1
Finland	Otaniemi	Triga
France	Cadarache Grenoble	LDAC Melusine Siloe
	Saclay	Osiris Isis Orphee
	Valduc	Mirene
Germany	Geesthact	FRG1 FRG2
	Karlsruhe	FR2
Italy	Casaccia	Triga
Netherlands	Petten	LFR HFR
Spain	Bilbao	ARB1
Sweden	Studsvik	R2 R2-0
U.K.	Aldermaston Harwell	Herald DIDO
Yugoslavia	Ljubijana	Triga

in France and the TRIGA reactors at Argonne and Hanford in the U.S.A.

There are those (the majority) where neutron radiography is only incidental to the main reactor program, but others, such

TABLE II

North America
Sample Neutron Radiography Projects

Country/State	Location	Reactor
CANADA	Chalk River	NRX
	Hamilton	MNR
UNITED STATES		
California	San Diego	G.A. MK1
	San Diego	G.A. MKF
	San Ramon	Aerotest
	Valecitos	GE-NTR
Georgia	Atlanta	GTRR
Idaho	Argonne	Treat
		Triga
New Mexico	Sandia	ACPR
Oregon	Corvallis	OSTR
Texas	College Station	Triga
Washington	Hanford	Triga

as the commercial AEROTEST and General Electric reactors in the USA which are supported primarily by income earned from neutron radiography.

Another obvious division is between the need primarily for inspection of reactor fuel and the need for inspection of non-radioactive objects.

Tables 1-3 list more detailed information on some of the many reactor based neutron radiography systems in various countries. Almost any research reactor can provide the base for a neutron radiographic facility, and these range from quite sophisticated to quite simple inexpensive systems. For those reactor operators or reactor users not able to attend the recent First World Conference on Neutron Radiography a number of points from these proceedings can usefully be summarised here.

TABLE III

Other Regions
Sample Neutron Radiography Projects

Country	Location	Reactor
Australia	Lucas Heights	Hifar MoatA
Brazil	Rio Sao Paolo	Argonaut 1 EAR-1
India	Bhabha Kalpakkam	Cirus APSara U-233 30KW
Indonesia	Bandung	Triga
Israel		
Japan	Jaeri Kyoto Univ	JRR-2 JRR-3 JRR-4 NSRR KUR
Mexico		
South Africa	Pelindaba	Safari 1
USSR	Auri	MR RBT-6 VVR Fast Reactor

IDEAS FOR REACTOR OWNERS

Diversity of Applications

Research reactor operators interested, challenging, and perhaps financially rewarding research projects should not overlook the rapidly expanding range of applications for neutron radiography. Significant progress has recently been reported, concerning neutron radiographic potential in such fields as biomedicine (Germany), Dentistry (France), Metallurgy (Yugoslavia), Engine Development (Britain) and Forensic Science (Canada). In the USA, techniques involving filtered beams

(University of Michigan), cold beams (G.A. Technology) pulsed beams (Oregon State University) and Computed Tomography (DOE) also indicate the range of promising research topics.

Inspection of Own Fuel

Reactor owners should also remain aware that neutron radiography can occasionally be useful for internal inspection needs. The classic example is that of the materials testing reactors for periodic inspection of in pile experiments. Other cases include use of the Oregon-TRIGA reactor to inspect its own reactor fuel by a combination of N-rays and X-rays.

Sale of Surplus Reactors

As times change the specific needs for research reactors change. In the last several years in the USA three TRIGA reactors have been acquired specifically for neutron radiography (two at Hanford and one at Argonne-West). Each has purchased second-hand reactor components. Universities whose needs for a teaching reactor have declined may wish to keep informed of future demand for transferred reactors for on-site neutron radiography.

SUMMARY

Neutron radiography is a small, but expanding field of application for research reactors. At a recent conference over 200 researchers from sixty (60) centers reported progress in a diversity of techniques. Neutron radiography plays a minor part in the programs of most reactors, and a dominant part in the role of some reactors. In Europe the use of existing reactors for neutron radiography of nuclear fuel is of major importance. In the USA neutron radiography is a driving force behind new research reactor installations and the possible sale of surplus reactors.

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USE AND DEVELOPMENT OF LOW AND MEDIUM FLUX RESEARCH REACTORS

Proceedings of the International Symposium on the Use and Development of Low and Medium Flux Research Reactors, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.

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NEUTRON RADIOGRAPHY WITH THE DR-1 REACTOR AT RISØ NATIONAL LABORATORY

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ABSTRACT

The Danish reactor No 1 (DR-1), a homogenous solution type, provides at maximum power of 2 kW two parallel neutron beams of 1.8 and 1.4 x 10^6 $n.cm^{-2}.s^{-1}$ at the object to be radiographed. This facility is used mainly for the control of irradiated nuclear fuel which is transported from Risø Hot Cells to the DR-1 in dual purpose transport/exposure containers. Routine neutron radiography is performed by using the transfer technique. Two exposures are made simultaneously on 4 x 12 cm Dy foils 100 μm thick. Typical examples of defects revealed in light water reactor fuel were chosen to produce a classification of defects, illustrated in a special atlas of reference radiographs. Risø has initiated standardization work within Euratom, where a Neutron Radiography Working Group was created, under Danish chairmanship. Beam purity and sensitivity indicators, and calibration fuel pins were designed and produced and are now used throughout Euratom NR centers to test the radiographic quality and accuracy of dimensional measurements from neutron radiographs.

RISØ DOUBLE-BEAM NEUTRON RADIOGRAPHY FACILITY

The DR-1, a homogenous solution type, designed by Atomics International, provides a maximum thermal neutron flux of 6.10^{10} $n.cm^{-2}.s^{-1}$ at maximum power of 2 kW. The spherical core tank has a diameter of 32 cm and is positioned at center of a graphite cylinder with a diameter of 152 cm (see fig. 1 and [1]). It was adapted for neutron radiography by removing from the reflector (1) two graphite blocks (3) positioned tangentially to the reactor core (2), thus permiting the neutrons to emerge through the reactor shielding as two beams of 1.8 and 1.4 x 10^6 $n.cm^{-2}.s^{-1}$ (at the object to be radiographed).

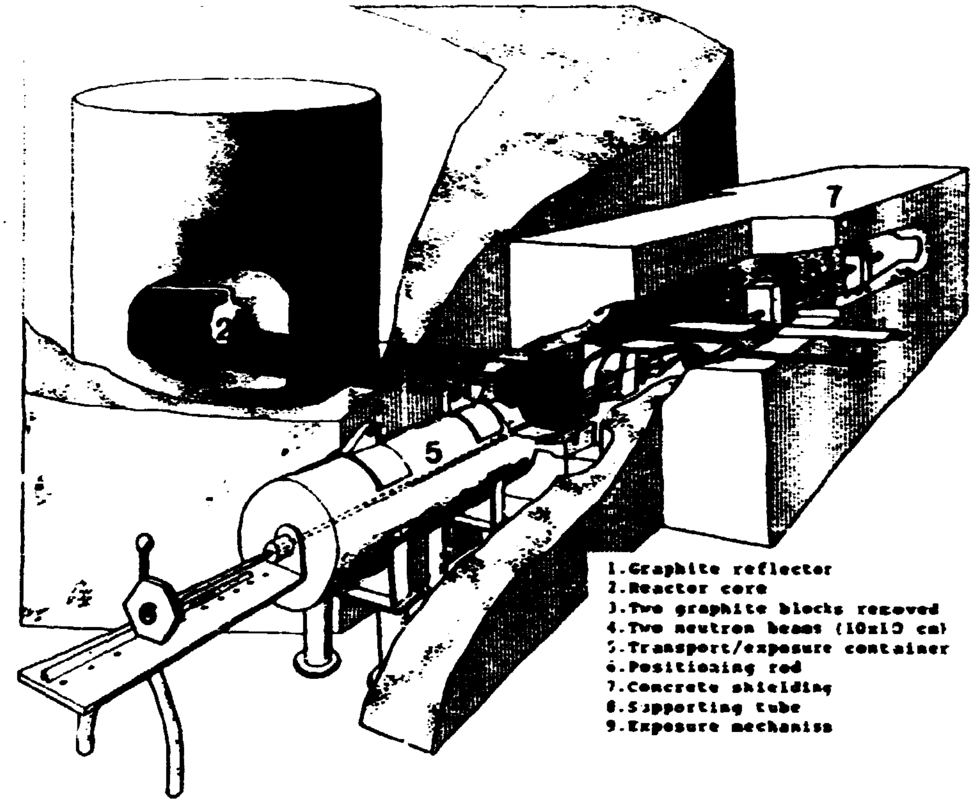

Fig. 1. Dual-beam neutron radiographic facility

The irradiated nuclear fuel rods are transported from the Hot Cells to the DR-1 in a dual purpose transport/exposure container (5). A steel rod (6) is attached to the back of this container, enabling the fuel rod (8) to be pushed out of the container and positioned in the two neutron ports. This part of the rod which has left the shielding container (5) enters a shielded enclosure made of concrete (7). The imaging foils are introduced behind the fuel rod by means of a mechanism (9) consisting of two curved guides, which accommodate the foils and press them toward the rod. The neutron beam, originates at the reactor core (2) and is collimated in the graphite collimator, having an inlet of 2 cm (vertically) x 8 cm (horizontally), and an outlet of 10 x 10 cm. The distance between the inlet point and exposure surface is 220 cm, which gives an L/D ratio of 110 (in the vertical direction). The cadmium ratio is 4.2 at the left port and 3.8 at the right.

Two transport/exposure containers are available: one to accomodate fuel rods up to 2.5 m in length and the other up to 4.5 m. The fuel rods are placed in a 1 mm thick Al tube, which protects the container from contamination and manipulates the fuel rod via a steel rod which is fastened to one of its ends and to which a square or hexagonalplate (6) can be affixed. Thus, a rotation in steps of 90° or 60° of the rod is possible.

EXPOSURE PROCEDURE

Neutron radiography is performed by the transfer method. A 100 µm Dy converter foil is used which is introduced through the guiding mechanism (9) to be in close contact with the fuel rod. After an exposure of about 30 min for Agfa Gevaert Structurix D4 film or 90 min for Kodak single-coated Industrex SR film, the Dy foil is removed from the exposure mechanism (9) and transported to the darkroom. Here X-ray film is placed at both sides of the foil and films and foil are inserted into a plastic vacuum casette. The films are exposed by the Dy foil overnight and are developed next day. The fuel rod is moved in 10 cm steps to radiograph its entire length.

At the bottom of each neutron port two cobalt wires are located which serve to provide a positioning index on each film. The developed films are eventually assembled in such a way as to give a single neutron radiograph of the whole fuel rod.

APPLICATION

The principal application of the Risø NR facility is the nondestructive examination of irradiated reactor fuel. Up till now the examinations have comprised 3 m long power reactor fuel rods as well as 15-200 cm long rods irradiated in test reactors. Rod diameters are in the range 10-15 mm. The irradiation exposure of those fuel rods ranges from 1,000 MWd/tU (a few weeks of irradiation) up to beyond 50,000 MWd/tU (corresponding to several years' exposure).

The purpose of radiographing irradiated fuel is to check the integrity of and detect/locate defects and dimensional changes in the fuel rod as a whole as well as its individual components. NR is used partly as a supplement to other nondestructive techniques, and partly for the characterization of features which would otherwise require destructive examination.

REFERENCE NEUTRON RADIOGRAPHS

During the assessment of neutron radiographs some typical defects of the fuel were found and it was felt that a classification of such defects will speed up the assessment procedure. Therefore, an attempt was made to establish such a classification. This classification was presented in [2].

As a contribution to the standardization work in the field of neutron radiography started in 1979 (under Danish chairmanship) by the Euratom Neutron Radiography Working Group (NRWG) this unique NR atlas will be published in 1983 in a revised and enlarged version in English and French [3]. It contains 158 neutron radiographs on film (original size) as well as on paper (twice enlarged) showing different fuel rod parts as fabricated and with different defects occurring in them. In particular cracks, chips, change of shape or location, voidage, inclusions and different nuclear properties in fuel itself are shown followed by defects in cladding (such as corrosion) and plenum. Finally defects in plugs and different instrumentation of the fuel pins are shown. The atlas contains also NR terminology in 6 languages (of the countries participating in NRWG).

QUALITY STANDARDS

For the sake of testing the radiographic image quality and accuracy of dimensional measurements from neutron radiographs of reactor fuel the NRWG has decided to produce and test special indicators developed for that purpose. They are the following: beam purity indicator BPI, beam purity indicator-fuel BPI-F, sensitivity indicator SI and calibration fuel pin CFP-El. Those indicators, fabricated at Risø were distributed among all NRWG participants and are tested under a special NRWG test program.

Beam Purity Indicators

The neutron beam and image system parameters that contribute to film exposure and thereby affect overall image quality can be assessed by the use of beam purity indicators, (fig. 2 and 3).

The beam purity indicator BPI was produced according to the ASTM standard [4]. For controlling the neutron beam components in nuclear fuel radiography the NRWG has developed a special beam purity indicator-fuel BPI-F which is a modification of the ASTM BPI. A key feature of the above devices is the ability to make a visual analysis of their images for subjective quality information. Densitometric measurements of the image of the devices permit quantitative determination of radiographic contrast, low-energy gamma contribution, pair-production contribution, image lunsharpness and information regarding film and processing quality.

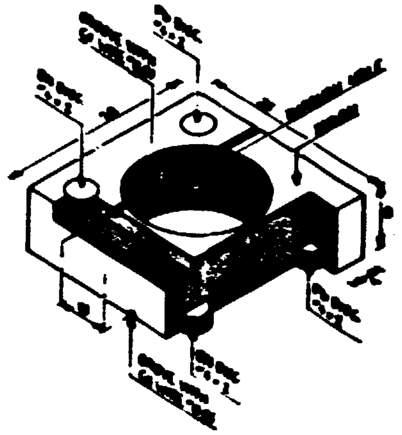

Fig. 2. Beam purity indicator BPI

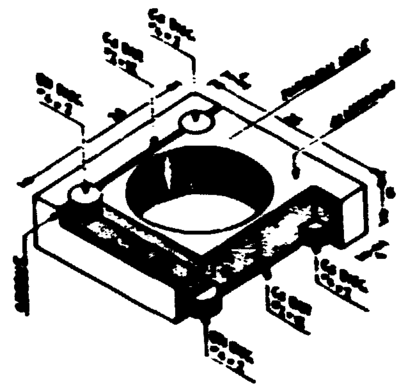

Fig. 3. Beam purity indicator-fuel BPI-F

Sensitivity Indicator

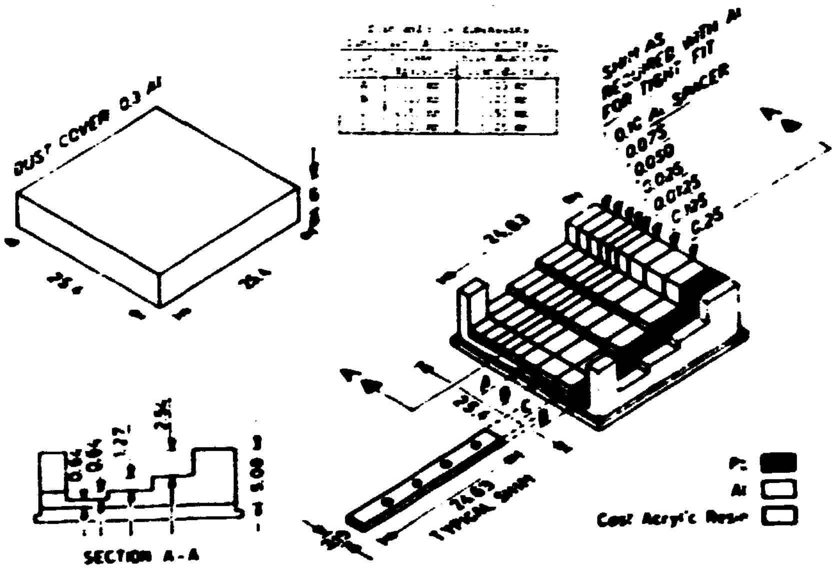

Fig. 4. Sensitivity indicator SI

The sensitivity indicator SI designed according to [4] (shown in fig. 4) basically combines a hole gage and gap gage into a small single device. The holes are sized to be smaller than can be seen by conventional neutron radiography, and they increase progressively in size. Similarly, the gaps, formed by Al shims between sheets of acrylic resin, cover a range that is useful for all facilities.

Calibration Fuel Pin

As mentioned in [4]: "It is recommended that the only truly valid sensitivity indicator is a material or component, equivalent to the part being neutron radiographed, with a known standard discontinuity (reference standard comparison part)". Such a "reference standard comparison part" for nuclear fuel pins is the calibration fuel pin CFP-E1, shown in fig. 4.

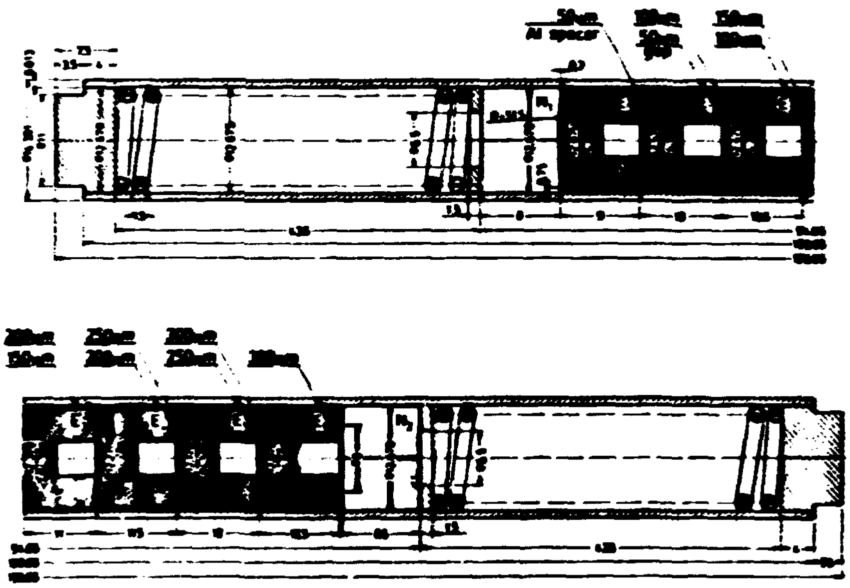

Fig. 5. Calibration fuel pin CFP-E1

From neutron radiographs of the CFP-E1 both axial as well as radial dimensions can be read. The results of those measurements shall be compared with true dimensions as given in the CFP-E1 certificate. Thus the accuracy of dimensional measurements from neutron radiographs can be determined.

NRWG Test Program

The beam purity indicators (BPI and BPI-F), sensitivity indicators (SI), and calibration fuel pins (CFP-E1) were sent to all members of the NRWG. They are tested under a special NRWG test program. Following its completion conclusions will be drawn about the adequacy of using of the particular indicators as quality standards for neutron radiography of nuclear fuel. It will also be possible to draw conclusions on the best methods and instruments to be used for accurately measuring the dimensions of nuclear fuel components from neutron radiographs.

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3rd European Conference on Nondestructive Testing

The official Conference of the:
European Societies for Nondestructive Testing

DEFECTS IN NUCLEAR FUEL REVEALED BY NEUTRON RADIOGRAPHY

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Summary

Like in other fields of industrial radiography it was necessary to classify defects revealed by neutron radiography and produce standard reference radiographs of different components of nuclear fuel, for which a classification of neutron radiographie findings was given. Neutron radiographie techniques used in the examination of nuclear fuel were reviewed Examples of neutron radiographie findings in pelletized, annular and vibro-compacted fuel, its cladding, plenum, plugs and instrumentation were given, extracted from a recently published collection of reference neutron radiographs prepared by the Euratom Neutron Radiography Working Group.

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*) Work performed under contract with Risø National Laboratory.

1. INTRODUCTION

In other fields of industrial radiography defects which can be revealed by radiography have been classified and reference radiographs, showing typical defects (e.g. in weldings or castings) have been completed and published long ago. No such classification nor reference radiographs did until recently exist in the field of neutron radiography.

The assessment of neutron radiographs of nuclear fuel elements can be much easier, faster and simpler if reference can be made to typical defects, which can be revealed by neutron radiography. Therefore it was felt that a classification of such defects will help to speed up the assessment procedure. Therefore an attempt was made by the Risø National Laboratory to establish such a classification.

Since 1974 neutron radiography is routinely used at Risø for the quality and performance control of nuclear fuel. During the post irradiation examination of light water reactor fuel typical defects of the fuel were found and a classification of those defects was made.

This classification together with a collection of 36 neutron radiographs illustrating those defects was published in 1979 in [1]. This atlas of neutron radiographs was presented as Risø's contribution to the Neutron Radiography Working Group (NRWG) constituted within the European Community in 1979. It was accepted by the NRWG as a first step of a more complete collection of neutron radiographs of nuclear reactor fuel with radiographs originating from all NRWG members. The Risø collection was further described in [2].

In 1982 a Sub-Group with the task of compiling a new edition of the reference neutron radiography collection was constituted within NRWG. As a result of the work of this Sub-Group "Reference Neutron Radiographs of Nuclear Reactor Fuel" were published in 1984 [3]. In this publication classification of neutron radiographic findings (in light water and fast reactor) is given together with 158 examples of defects* in nuclear fuel as well as its different parts as fabricated. The text of this collection is produced both in English and French. Special terms used throughout the collection as well as some useful ones in the field of neutron radiography, are given in Danish, Dutch, English, French, German and Italian.

Some of the neutron radiographs of nuclear fuel were reproduced also in [4].

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*) The term "defect" is used to designate a change in appearence shown on an original radiograph of a particular part of the fuel as fabricated, to that shown on a subsequent radiograph, usually post irradiation.

2. FUEL COMPONENTS

Some typical examples of nuclear fuel pins are given on fig. 1 where all the components of the pins are listed. They represent pelletized, annual and vibro-compacted fuel.

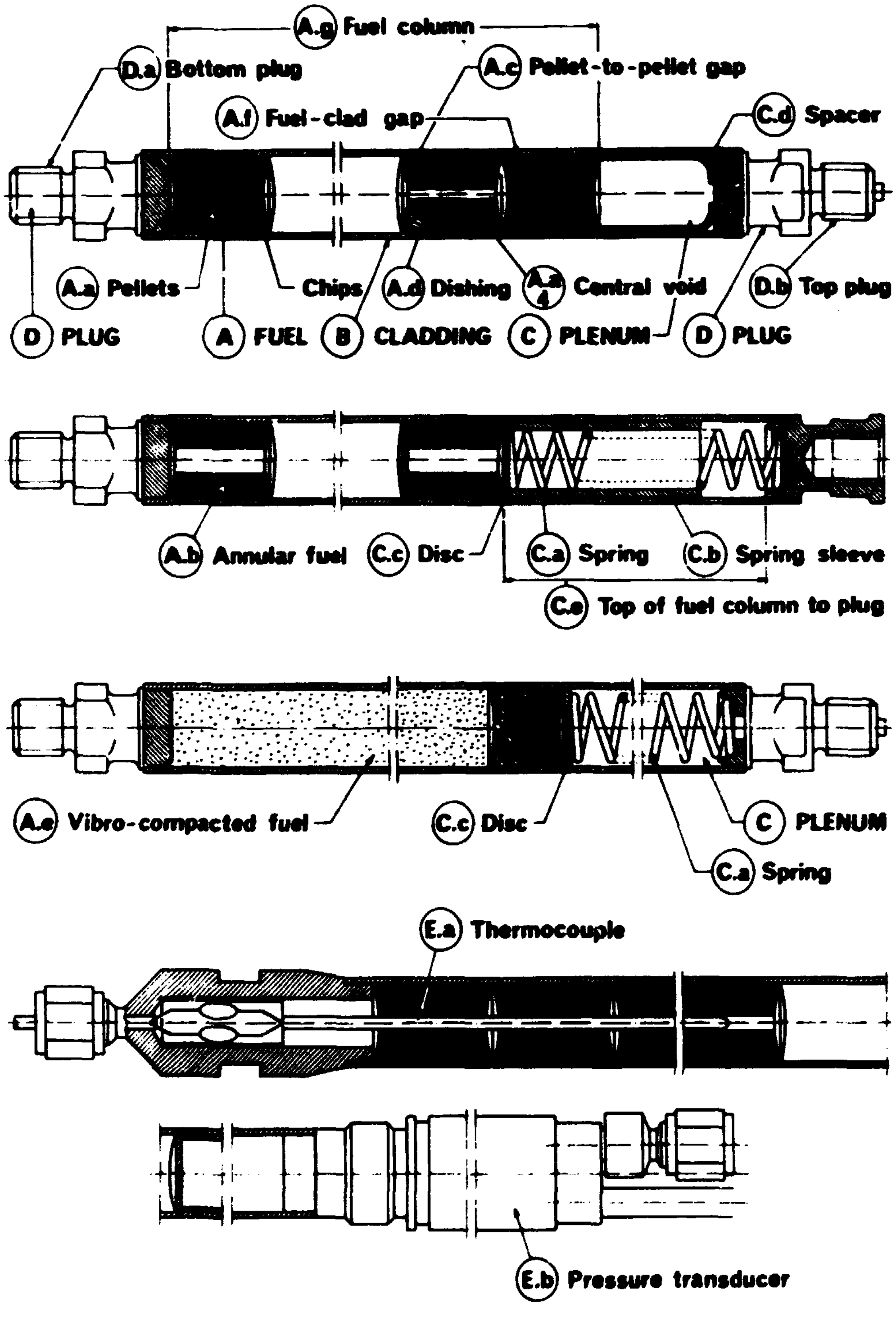

Fig. 1. Examples of nuclear fuel pins

3. CLASSIFICATION OF NEUTRON RADIOGRAPHIC FINDINGS

The classification of different findings on neutron radiographs of nuclear fuel, adopted by the NRWG, is listed below:

0. (Fuel pin part)AS FABRICATED

1. CRACKS
1.1 Random
1.2 Longitudinal
1.3 Transverse
1.4 Annular
1.5 Stratified

2. CHIPS
2.1 Corner
2.2 Other
2.3 In pellet-to-pellet gap
2.4 Missing

3. CHANGE OF SHAPE OR LOCATION
3.1 Enlarged or swollen
3.2 Contracted
3.3 Filled-up or closed
3.4 Deformed
3.5 Broken
3.6 Dislocated
3.7 Extended
3.8 Accumulated
3.9 Restructured
3.10 Melted
3.11 Disintegrated
3.12 Migrated

4. VOIDAGE
4.1 In one pellet
4.2 Through several pellets
4.3 Through whole fuel column

5. INCLUSIONS
5.1 Of Plutonium
5.2 Of poison
5.3 Other

6. CORROSION
6.1 Hydrides
6.2 Oxides
6.3 Other

7. NUCLEAR PROPERTIES
7.1 Different enrichment
7.2 Different burn-up

8. COOLANT
8.1 Present
8.2 Absent

4. NEUTRON RADIOGRAPHIC TECHNIQUES

In neutron radiography performed with silver-halide films (X-ray films) two exposure techniques are used: the direct and the transfer technique. The first is used for non-radioactive objects, whereas the second must be used for radioactive ones (such as e.g. irradiated nuclear fuel). For radioactive objects the nitrocellulose film and the track etch technique gives the best results. The principles of all those three techniques are shown on fig. 2.

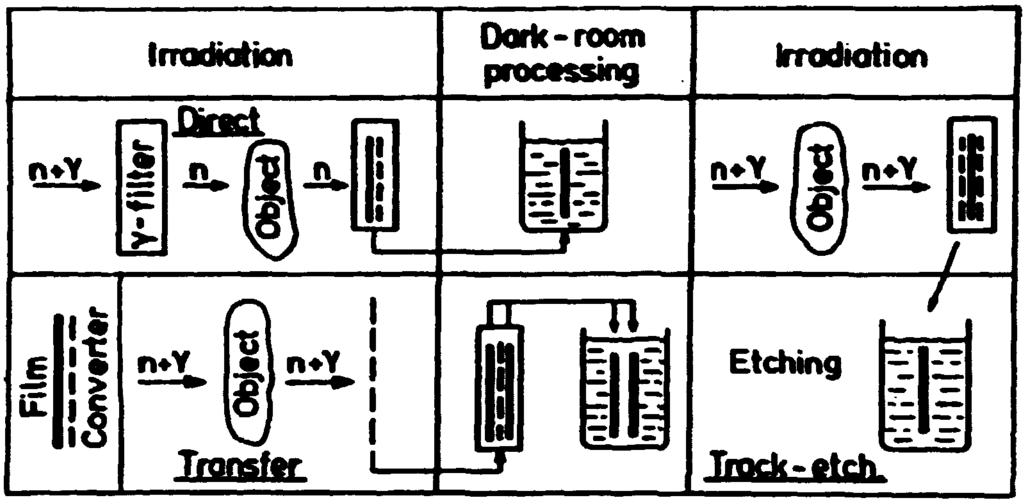

Fig. 2. Neutron radiographic techniques

All the above techniques were used in the NRWG collection [3]

5. EXAMPLES OF NEUTRON RADIOGRAPHIC FINDINGS

From 158 neutron radiographic findings assembled in [3] some typical examples are given below (as enlargements of original radiographs on film).

On fig. 3 examples of pelletrized fuel are given, whereas fig. 4 shows annular fuel, and fig. 5 vibro-compacted fuel. Cladding is shown on fig. 5, plenum on fig. 7, plug on fig. 8 and instrumentation on fig. 9. As in the collection [3] the examples include also radiographs of nuclear fuel as fabricated (before irradiation). Thus it is easier to identify the changes which have occured in the fuel during irradiation.

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[1] J.C. Domanus. Neutron radiographic findings in light water reactor fuel. Risø National Laboratory,Metallurgy Department June 1979.

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[3] J.C. Domanus, (editor). Reference neutron radiographs of nuclear reactor fuel. D. Reidel Publishing Co. EUR 9816 EN EP. 1984.

[4] J.P. Barton. Implementation of neutron radiography. The Non-destructive Testing Handbook on Radiography and Radiation Testing. Section Thirteen. ASNT, Columbus, Ohio. 1984.

Fig.3a. Pelletized fuel as fabricated

Fig.3b. Random cracks in pellets

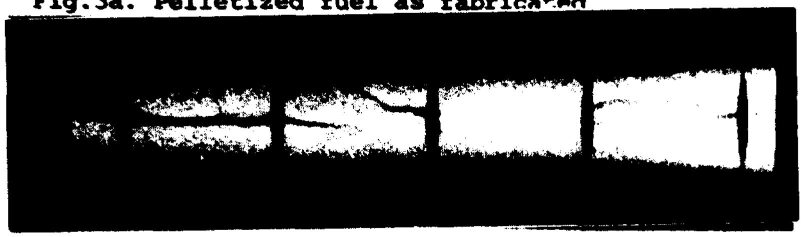

Fig.3.c. Longitudinal cracks in pellets

Fig.3d. Central void in one pellet

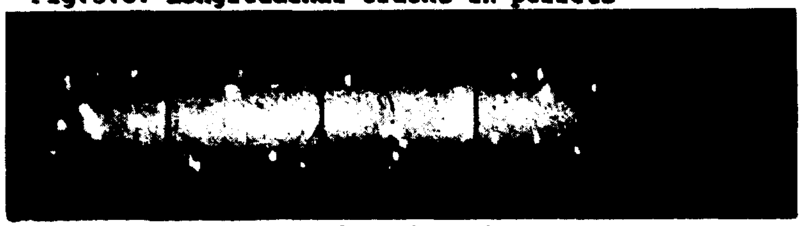

Fig.3e. Inclusions of Pu in pellets

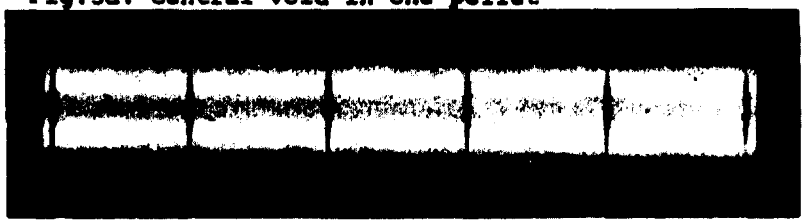

Fig.4a. Annular fuel as fabricated

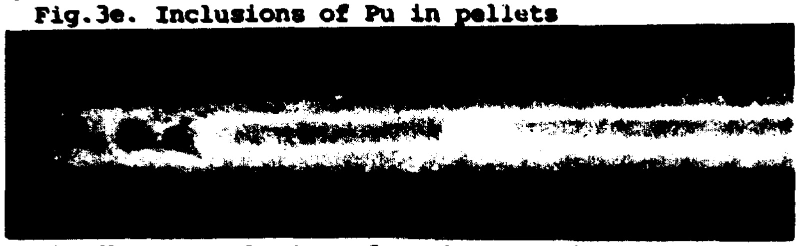

Fig.4b. Accumulation of Pu in central void

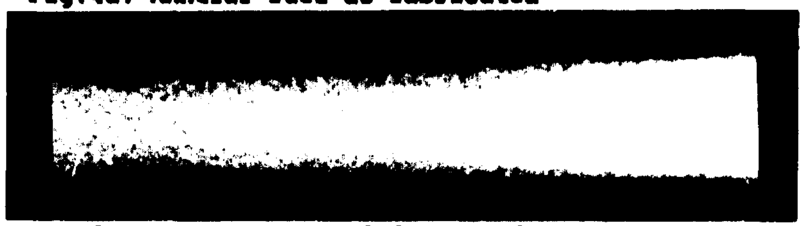

Fig.5a. Vibro-compacted fuel as fabricated

Fig.5b. Missing chips in vibro-compacted fuel

Fig.6a. Deformed cladding

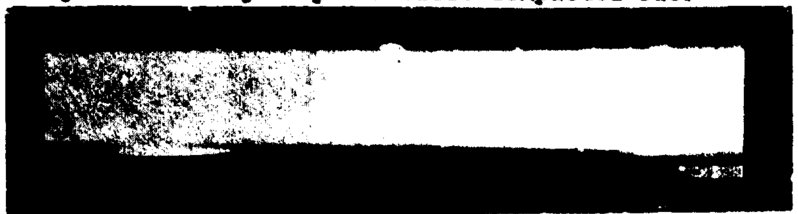

Fig.6b. Hydrides in cladding

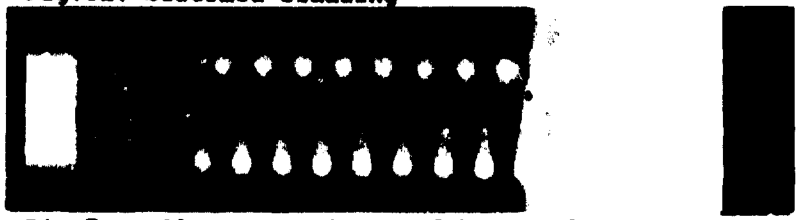

Fig 7a. Plenum. Spring as fabricated

Fig.7b. Plenum. Dislocated insulating disc

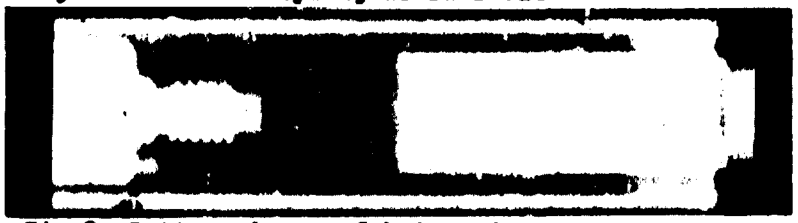

Fig.8. Bottom plug as fabricated

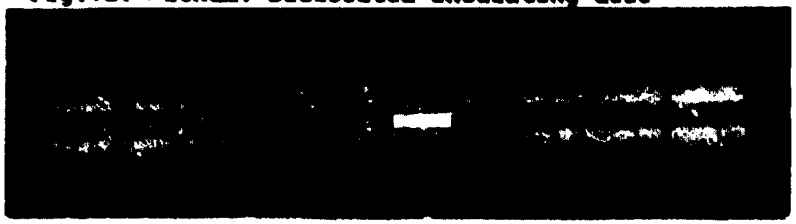

Fig.9a. Melted thermocouple

Fig.9b. Diameter gauge as fabricated

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NEUTRON RADIOGRAPHIC TECHNIQUES, FACILITIES AND APPLICATIONS by J. C. Domanus	Department or group METALLURGY Group's own registration number(s)
28 pages + 3 tables + 26 illustrations	
Abstract (see below)	Copies to

Abstract

This is a collection of three papers, written for presentation on two international conferences.

The first paper: "Neutron radiography. Techniques and facilities", written by J. P. Barton of N-Ray Engineering Co. La Jolla, CA, USA and J.C.Domanus was presented at the International Symposium on the Use and Development of Low and Medium Flux Reactors at the Massachusets Institute of Technology, Cambridge, Mass. USA, 16-19 October 1983.

The second paper.: "Neutron radiography with the DR-1 reactor at Risø National Laboratory" written by J. C. Domanus, was presented at the same Symposium.

The third paper: "Defects in nuclear fuel revealed by neutron radiography", written by J. C. Domanus is accepted for presentation on 18 October 1984 to the 3rd European Conference on Nondestructive Testing, Florence, Italy, 15-18 October 1984.

While the first paper describes the principles of neutron radiographic techniques and facilities, the second one describes an example of such facility and the third gives an example of application of neutron radiography in the field of nuclear fuel.

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